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Journal of Electron Spectroscopy and Related Phenomena 127 (2002) 37–41

JOURNAL OF ELECTRON SPECTROSCOPY and Related Phenomena

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Coupling of quasiparticles to phonons in high temperature superconductors

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Abstract

A detailed study of the quasiparticle excitations by angle resolved photoemission spectroscopy is reported in three different families of high temperature superconductors. The data show the coupling of quasiparticles to phonons in the range of 50–80 meV. The effect persists above the critical temperature and shows a slight decrease as we increase doping.

Keywords: ARPES; Electronic structure; Quasiparticles; Collective mode; Scattering rate

1. Introduction

Since the advent of high-temperature superconductivity, angle resolved photoemission spectroscopy (ARPES) has been one of the most powerful techniques to understand the microscopic phenomena of Cu-oxide superconductors. Among the biggest discoveries we recall the superconducting gap and the symmetry of the order parameter, the pseudogap in the normal state, and the determination of the normal state Fermi surface [1]. During the last years a big effort has been invested for an improvement of this technique toward new limit for the energy and momentum resolution. A detailed study of the quasiparticle lifetime and dispersion, which are directly related to the ARPES signal, can in fact shed light into the many-body character of the electronic excitations, which are a very important issue in understanding the physical properties of a material. For example, the identification of the phonon anomalies in the electronic tunneling spectra of metal, have played a decisive role in our understanding of conventional superconductors [2]. Driven by the desire to understand the low-energy excitations in high-temperature superconductors we studied three different families of oxide cuprates.

In this paper we report comprehensive ARPES data from Pb-doped $Bi_2Sr_2CaCu_2O_8$ (Pb-Bi2212), Pb-doped $Bi_2Sr_2CuO_6$ (Pb-Bi2201) and $La_{2-x}Sr_xCuO_4$ (LSCO) systems. We found evidence of coupling of the quasiparticle to a collective mode. The coupling to the mode manifests itself both in the quasiparticle dispersion, and in the quasiparticle

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0368-2048/02/$ – see front matter
PII: S0368-2048(02)00170-6

lifetime, showing a drop of the scattering rate at the mode energy. The collective mode has an energy scale of 50–80 meV, is ubiquitous and persists above the critical temperature. The coupling strength is big and gets weaker increasing doping. After a detailed analysis we could identify the nature of the observed behavior as due to the lattice-phonons and/or charge inhomogeneities. Furthermore we found that the phenomenology is similar to the longitudinal optical (LO) phonons associated with local charge inhomogeneity, providing clear evidence of a role for spatial inhomogeneity in charge dynamics.

2. Experimental

The Pb-Bi2212, Pb-Bi2201 (overdoped, T_c=7 and underdoped T_c=10 K) and LSCO data have been recorded at beam-line 10.0.1.1 of the Advanced Light Source (ALS), utilizing 55 eV photon energy. The Pb-Bi2201 (overdoped, T_c=5 K) data have been recorded at the beam-line 5.4 of the Stanford Synchrotron Radiation Laboratory (SSRL) with unpolarized He–I light from a He lamp (hn=21.2 eV). In the ALS experimental geometry the samples were kept in a fixed position relative to the beam polarization and the analyzer was rotated. The experimental geometries are the same as those reported before [3,4]. We used a Scienta analyzer SES 200 in the angular mode where cuts parallel to the nodal (G–Y) direction are carried out. For the 55 eV data, the momentum resolution was 0.006 A^{-1} in the scan direction and 0.019 A^{-1} in the perpendicular direction, and the energy resolution was 18 meV. The energy and momentum resolution for the 22 eV photon energy data was 10 meV and 0.008 A^{-1}, respectively. The vacuum during the measurement was better than 6×10^{-11} Torr (1 Torr=133.3222 Pa). The single crystalline Bi2212 samples overdoped (OD) Pb-Bi2212 (T_c=82.5 K; Pb doping 11 of Bi sites); optimally doped (opt) Bi2212 (T_c=91 K) and underdoped (UD) Bi2212 (T_c=84 K) were oriented and cleaved in situ at 100 K. The single crystalline Pb-Bi2201 samples (OD T_c=7 K, T_c=5 K and underdoped T_c=10 K) were oriented and cleaved in situ at 30 K. The single crystalline LSCO samples OD (x=0.22), opt (x=0.15) and UD (x=0.07) were oriented and cleaved in situ at 20 K. All the samples were grown using the floating-zone method.

3. Results and discussion

3.1. ARPES spectra: extraction of the quasiparticle lifetime and dispersion

ARPES is a powerful tool to obtain direct information on the quasiparticle spectral function $A(k, \omega)$, because the photoemission signal is directly proportional to $A(k, \omega)$. The spectral function is related to the self-energy through the following relationship:

$$A(k,\omega)=\frac{1}{\pi}\cdot\frac{\mathrm{Im}\,\Sigma(k,\omega)}{[\omega-\varepsilon(k)-\mathrm{Re}\,\Sigma(k,\omega)]^2+[\mathrm{Im}\,\Sigma(k,\omega)]^2} \quad (1)$$

where $\varepsilon(k)$ is the dispersion of the electrons in the absence of interactions while $\Sigma(k, \omega)$ is the self-energy which includes the many-body effects. The traditional way to extract information on the quasiparticle dispersions from photoemission spectra, is to analyze the data as a function of energy (E) at a fixed momentum (k), the so-called energy distribution curves (EDCs) (Fig. 1c). Recent advances in analyzer technology have allowed one to probe the electronic states with a much higher precision in the momentum state. New information can be obtained from an analysis of the data for fixed binding energy as a function of momentum, i.e., momentum distribution curves (MDCs) (Fig. 1b). A schematic view of the energy and momentum distribution curves is shown in Fig. 1.

Since the self-energy Σ typically depends more strongly on energy than on momentum, the MDCs have a lorentzian lineshape, with a width proportional to the inverse of the quasiparticle lifetime. This allows a simple fit of data by using lorentzian functions. Of course the information we extract from the MDCs and EDCs are consistent with each other.

The quasiparticle dispersions and scattering rate reported in this paper have been extracted from the MDC analysis, a general approach now used in the

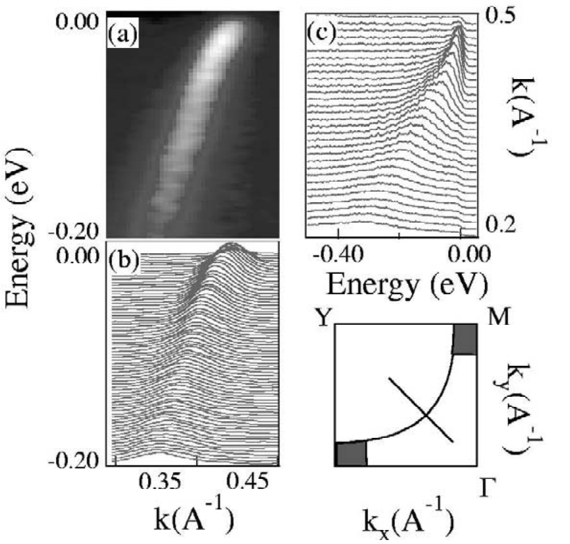

Fig. 1.

case of photoemission experiments of strongly correlated systems, where the EDCs are complex functions and not simple lorentzians.

3.2. Evidence of an energy scale in cuprates superconductors

The data reported in this paper have been collected along the nodal direction Γ–Y, also called [(0, 0) to (π, π); see Fig. 1d], where, the superconducting gap is zero. This choice is justified by the fact that, especially in the case of Bi-based cuprates, as we move away from the nodal direction, many other contributions such as superstructure from the BiO planes, the bilayer splitting and the opening of the superconducting gap start to play a role [5], making trivial the extraction of the quasiparticle dispersion.

In Fig. 2a–c we report the quasiparticle dispersion in the range from zero to 200 meV binding energy for different cuprate oxides and at different doping. The rescaled dispersions fall together displaying a similar behavior at the different dopings for each systems. The quasiparticle dispersion is am linear function of momentum in the studied range, however, an abrupt change (kink) appears at low binding energy. A similar phenomena has been reported previously in the case of Bi2212 systems by different groups [3,6,7]. The direct comparison between the

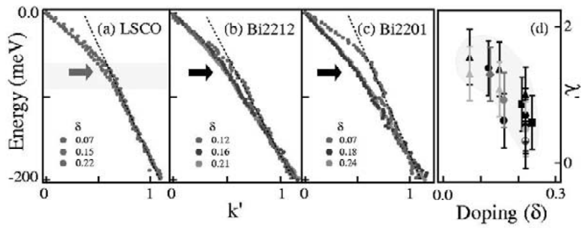

Fig. 2. ARPES spectra (hn = 21.2 eV; T = 13 K) of the 2D Fermi liquid system $TiTe_2$ near the Fermi surface crossing along the high symmetry ΓM direction in the Brillouin zone. The dashed line is the spectrum measured at the Fermi wavevector.

three systems suggests the presence of a similar phenomena relevant to the quasiparticle dynamics and highlights the existence of a common energy scale in the range as 50–80 meV, although it is possible to have small variation from system to system. A detailed analysis shows a slight decrease of this mode energy for the overdoped samples. The presence of the energy scale is likely a manifestation of many-body effects. In Fig. 3a–c we report the temperature dependence of the kink for the optimally doped LSCO, optimally doped Bi2212 and underdoped Bi2201. In systems like Bi2201 and LSCO the effect persists at temperature much higher than T_c (of course the T_c in these systems is fairly low). In the case of Bi2212, the effect appears to be smeared out at higher temperatures, because of the higher T_c of this material.

The similar energy scale of this excitation (50–80

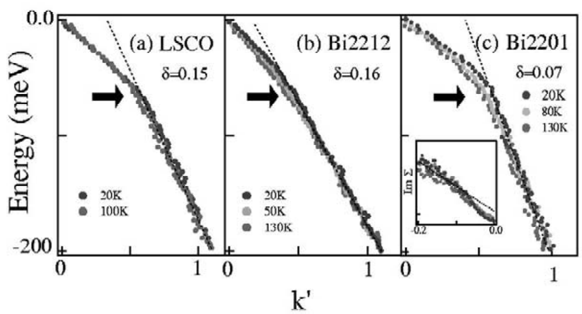

Fig. 3. Temperature dependence of the dispersion along the nodal direction for LSCO (a, optimally doped), Bi2212 (b, optimally doped) and Bi2201 (c, underdoped). The kink persists above the critical temperature and is smeared at high temperature by thermal broadening. At the phonons frequency the scattering rate shows a drop which persist above the critical temperature (inset of panel c).

meV) in systems with very different gap energy, ranging from (10 to 20 meV) for LSCO and Bi2201, to (40–50 meV) for Bi2212, rules out the superconducting gap as having any role in the observed phenomena. Our observation also rules out the other proposed explanation [6,8] in terms of coupling with the magnetic mode at 41 meV [9,10], because of the observation of the kink in the LSCO, where the magnetic mode does not exist. The persistence of the kink above the critical temperature further rules out this interpretation, because the magnetic mode sets in at T_c for optimal and overdoped samples [9].

In the context of a quasiparticle interacting with collective modes, the only two surviving candidates seem to be phonons or charge inhomogeneities, which are in some sense related in these systems. ARPES data from systems with a strong electron–phonon interaction display a behavior similar to the one we observe, showing a change in the dispersion for energies close to the phonon frequency [11,13]. The phonon interpretation [14] receives strong support from a direct comparison between photoemission results and neutron scattering data on LSCO. As shown by the red arrow and the shaded area in Fig. 2a, the energy of the zone boundary in-plane oxygen stretching LO phonon, identified by neutron as being strongly coupled to charge [15], coincides with the ''kink'' energy in our data, baring minor correction with the small superconducting gap of 10 meV. We identify this mode as the highest energy phonon that strongly contributes to the ARPES data. However, other phonon contributions should be included as, for example, the apical mode [17] related to the in plane oxygen-stretching mode [16]. Based on neutron experimental data and lattice model calculations these phonons are believed to be related to local charge inhomogeneity [15]. The presence of such lattice-phonons is also indicated by other experiments [18].

In the context of quasiparticles interacting with phonons we should expect, apart from a kink in the dispersion, a drop in the scattering rate (i.e., Im Σ) at the phonon frequency. This has been observed in all the materials we studied. An example of this is shown in the inset of Fig. 3c for the Bi2201. However the behavior of the scattering rate at high frequency suggests an important contribution coming from the electron–electron interactions, in addition to the electron–phonon interactions [19].

A discontinuity in the Im Σ is translated into a change of the spectral function $A(k, \omega)$, related by Eq. (1), and this is manifested in the presence of a double feature peak in the energy distribution curves, peak–dip–hump structure, where the dip occurs approximately at the phonon energy. This behavior has been demonstrated both theoretically, in the case of quasiparticles coupled to phonons [13], and experimentally.

In Fig. 4 we report the energy distribution curves at different doping for the Bi2212 system along the nodal direction and for underdoped Bi2201. The data are compared with data in the literature on the Be system [11]. A clear resemblance between them, in agreement also with what one would expect in the case of quasiparticle interacting with phonons, further supports the interpretation of coupling to phonons. In panel (d) we report data for the Bi2201 above the critical temperature. The data show clearly that the effect is visible above the critical temperature even in the EDCs. We recall here that the disappearance of the peak–dip–hump structure above the critical temperature has been a long standing debated point, used against the phonon interpretation. The data on Bi2201, where the critical temperature is very low has allowed us to study this effect without the problem of thermal broadening, which strongly affects the EDCs.

Lastly, we want to investigate how the coupling constant changes as a function of dopings. In a simple model of electron–phonon coupling, the coupling strength is inversely proportional to the ratio of the velocity change between the dressed electrons and the bare velocity. In our case, following a similar assumption, we can extract quantitative

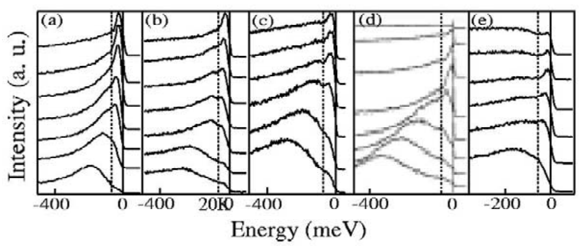

Fig. 4. (a–c) Energy distribution curves along the nodal direction for the Bi2212 systems at different dopings. The data are compared with the EDCs of the Be system (d). The data show a clear resemblance. In panel (e) we report the EDCS of the Bi2201 systems above the critical temperature ($T = 20$ K).

information from the ratio between the bare quasiparticle velocity (which in this case can be approximated by the high energy part of the dispersions) and the dressed velocity (low energy part). The two velocities are extracted from our data fitting the experimental dispersions with two straight lines. The doping dependence of the coupling strength is reported in Fig. 2d. One can see that the velocity changes by more than a factor of two, indicating a very strong coupling. A slight increase of the ratio is observed moving toward the UD region. Of course the λ experimentally determined is an overestimate of the real electron–phonon coupling constant because the high-energy dispersion is an overestimate of the bare velocity and because the electron–electron scattering influences the dispersion away from the phonon energy.

4. Summary

ARPES results obtained with high energy and momentum resolution are reported for different families of cuprates superconductors. The quasiparticle dispersion and scattering rate for the different systems has been studied in detail. The data are consistent with each other and support the coupling of quasiparticles to a collective mode, at a similar energy for different systems. An accurate analysis of the phenomena as a function of temperature and doping and a direct comparison with neutron scattering data on similar material suggest that the quasiparticles in high temperature super-conductors are strongly coupled to phonons. This result points toward phonons as a key ingredient in any microscopic mechanism of high temperature superconductivity.

References

[1] Z.X. Shen, D. Dessau, Phys. Rep. 253 (1995).
[2] D.J. Scalapino, in: R.D. Parks (Ed.), Superconductivity, Marcel Dekker, New York, 1969, and references therein.
[3] P.V. Bogdanov et al., Phys. Rev. Lett. 85 (2000) 2581.
[4] X.J. Zhou et al., Phys. Rev. Lett. 86 (2001) 5578.
[5] D.L. Feng et al., Phys. Rev. Lett. 86 (2001) 5550; Y.D. Chuang et al., Phys. Rev. Lett. 87 (2001) 117002; P.V. Bogdanov et al., Rapid Commun. in press.
[6] A. Kaminski et al. 86 (2001) 1070.
[7] T. Valla et al., Science 285 (1999) 2110.
[8] M. Eschrig, M.R. Norman, Phys. Rev. Lett. 85 (2000) 3261.
[9] H. He et al., cond-mat 0002013 (2000).
[10] H.F. Fong et al., Phys. Rev. B 54 (1996) 6708; J.P. Carbotte, Nature 401 (1996) 354.
[11] M. Hengsberger et al., Phys. Rev. Lett. 83 (1999) 592; S. Lashell et al., Phys. Rev. B 61 (2000) 2371.
[13] T. Valla et al., Phys. Rev. Lett. 83 (1999) 2085.
[14] A. Lanzara et al., Nature 412 (2001) 510.
[15] R.J. McQueeney et al., Phys. Rev. Lett. 82 (1999) 628; Y. Petrov et al., cond-mat 0003414 (2000).
[16] A. Bianconi et al., Phys. Rev. Lett. 76 (1996) 3412.
[17] M.A. Quijada et al., Phys. Rev. B 52 (1995) 15485.
[18] A. Bianconi, M. Missori, Solid State Commun. 91 (1994) 1; N.L. Saini et al., Phys. Rev. B 55 (1997) 12759; K.A. Muller, J. Superconductivity 12 (1999) 3; A. Lanzara et al., J. Phys. Cond. Matter 11 (1999) L541; D. Mihailovic, V.V. Kabanov, cond-mat 0010189 (2000); S. Billinge et al., Phys. Rev. Lett. 72 (1994) 2282; H. Mook et al., Nature 401 (1999) 145.
[19] X.J. Zhou et al., unpublished.